Machinery Messages

Case History

Reactor recirculation pump shaft crack

by Jeffrey S. Bohanick
Systems and Performance Engineer
Grand Gulf Nuclear Station
Systems Energy Resources, Inc.
and Richard Thomas, P.E.
Senior Machinery Diagnostic Services Engineer
Bently Nevada Corporation

THIS case history documents a significant save of a nuclear reactor recirculation pump and motor. A crack propagated through the pump shaft in the general area of the hydrostatic bearing between 1 and 11 May, 1989. Driven by a 7,940 horsepower motor, each reactor recirculation pump can pump approximately 45,000 gallons per minute (170,325 liters/min) of water to the reactor core. The reactor recirculation pumps are permanently monitored for vibration using proximity probes to measure shaft relative displacement, axial vibration and shaft rotative speed. These pumps are also monitored for flow rate, bearing temperature and motor winding temperatures.

On 11 May, a Vibration Engineer at Grand Gulf Nuclear Station performed routine monitoring and vibration checks on all the continuously monitored critical rotating machinery. Unfiltered and filtered Orbit displays and overall amplitudes from the vibration monitors were used for this routine monitoring and vibration check. All amplitudes were nearly identical to data observed two weeks previously under similar operating conditions.

A half hour later, however, the Orbit pattern on the B reactor recirculation pump changed. Amplitudes measured with proximity probes, located at the pump coupling, increased from 13 mils (330 μm) peak-to-peak to 16 mils (406 μm) peak-to-peak. Thirty minutes later, the vibration at the pump coupling had reached 18 mils (457 μm) peak-to-peak. Proximity transducers located at the motor inboard bearing, motor outboard bearing and motor axial vibration locations all exhibited an increase in vibration levels as well. At this time, the Vibration Engineer was actively collecting vibration frequency spectrum data and correlating process and vibration data to determine if process changes were responsible for the increase in vibration.

Vibration spectra, coupled with the process data, verified that process conditions were not responsible for the increase in vibration. The Vibration Engineer, convinced that an imminent problem requiring machinery shutdown was in progress, started recording the vibration signals on both recirculation pumps with an instrument-grade tape recorder and notified the control room operators of the high vibration observed on the B recirculation pump.

Vibration vector data revealed that the increases in vibration were at the 1X and 2X frequencies with corresponding significant 1X and 2X phase shifts. A half hour later, the vibration levels had increased above the Danger setpoint of 20 mils (508 μm) peak-to-peak. Operations personnel adjusted the flow control valve to try to reduce the vibration trend. These efforts were futile and the vibration increased to 30 mils (762 μm) peak-to-peak. Three hours after the initial change in the shaft Orbits was observed, the pump was secured at slow speed and the overall pump coupling vibration amplitude decreased to 11 mils (279 μm) peak-to-peak. The recirculation loop operated at slow speed with continuous vibration monitoring and loose parts monitoring in order to provide time for the data to be reviewed and to allow for further data collection.

After looking at data the next day, it was apparent that the pump had been damaged and that any further operation of the pump, even at slow speed, would not be prudent. The pump was shut down and the vibration, loose parts "noise" and process data were carefully reviewed. Vibration data indicated that the excessive vibration was due to a pump shaft crack and/or a bent shaft.

Visual inspection revealed several things. First, that the shaft had a visible crack approximately 320 degrees in circumference in the tapered shaft section immediately above the impeller attachment weld. Secondly, that the upper part of the hydrostatic bearing had a 360 degree rub mark and that the bearing journal had a 130 degree wear mark. And lastly, that the shaft was bent relative to the shaft centerline.

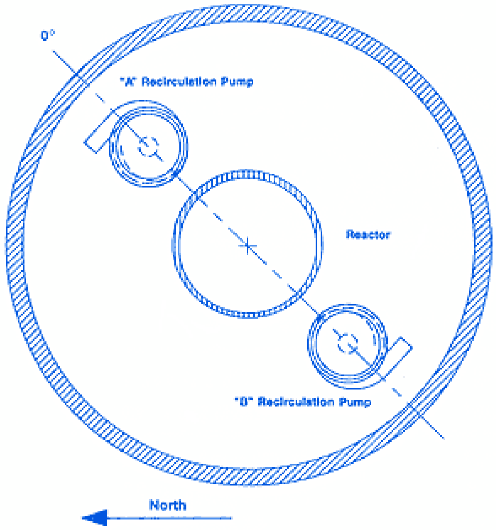

Figure 1
Reactor recirculation pump showing vibration transducer orientation

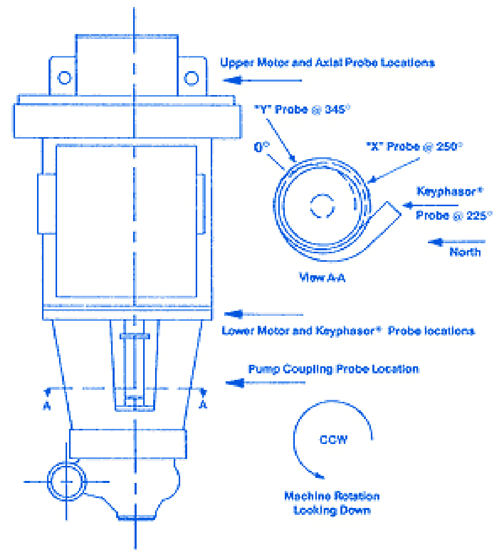

Figure 2
Reactor recirculation pump showing probe location

Recirculation pump arrangement

The general arrangement of the A and B reactor recirculation pumps is depicted in Figure 1. This figure also defines the angular locations of the vibration transducers for the two rotor systems with respect to an arbitrary 0 degree reference.

On each of the two rotor systems there are three sets of XY proximity probes at the following locations:

1) Upper Motor Bearing (UMB Y and UMB X)

2) Lower Motor Bearing (LMB Y and LMB X)

3) Pump Coupling Hub (PCH Y and PCH X)

Additionally, each pump is equipped with a single axial position transducer, observing a balance ring near the upper motor bearing and a Keyphasor® transducer located near the lower motor bearing (Figure 2). The Keyphasor® transducer signal was used as the reference for all phase data presented in this article.

Diagnostic approach

An analysis of the Grand Gulf taped data was conducted to evaluate whether or not indications of a shaft crack were apparent prior to reducing the pump to low speed operation. The analysis was based on the following basic interpretation of shaft crack phenomena.

A shaft with a crack experiences a degredation of stiffness in the plane of the crack. Therefore, when subjected to a radial force, the shaft with a crack will bow more than the shaft without a crack. In addition, the shaft with the crack will exhibit a different dynamic response both during steady state and during transient (startup/coastdown) operating conditions. In the case of a horizontal machine, the most common source of a steady state force is gravity.

In a reactor recirculation or a reactor coolant pump, radial side loads and/or severe misalignment of the motor and pump shafts provide the necessary radial force. The crack creates a bowed condition, indicated by a change in the 1X response and an asymmetric rotor stiffness, creating a 2X response. The 1X and 2X vibration response vectors thus became the key indicators of potential cracks.

The data for the recirculation pump was acquired during throttled operation with the flow control valve opened from 6% to 12%. In this condition, a net radial side load exists at the impeller periphery, acting away from the throat of the pump, i.e. toward the east.

Steady state data

Figures 3 through 10 show that the unfiltered, 1X filtered and 2X filtered shaft Orbits had not changed in either magnitude or phase through 2 May. However, the data for 11 May clearly shows that significant amplitude and phase changes had occurred in all orbital presentations. ►

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The relative changes in amplitudes from 1 May to 11 May are as follows:

1 May

Location Unfiltered mils pp (μm)	1X Filtered mils pp (μm)	2X Filtered mils pp (μm)
UMB Y 5.69 (144 μm)	2.48 (63 μm) at 259°	0.36 (9 μm) at 238°
LMB Y 13.41 (341 μm)	3.52 (89 μm) at 125°	2.19 (56 μm) at 273°
LMB X 9.69 (246 μm)	3.05 (77 μm) at 67°	2.10 (53 μm) at 175°
PCH Y 17.52 (445 μm)	14.07 (357 μm) at 323°	0.62 (16 μm) at 157°
PCH X 16.92 (430 μm)	11.75 (298 μm) at 199°	0.51 (13 μm) at 16°

11 May

Location Unfiltered mils pp (μm)	1X Filtered mils pp (μm)	2X Filtered mils pp (μm)
UMB Y 7.77 (197 μm)	5.04 (128 μm) at 244°	0.36 (9 μm)at 238°
LMB Y 21.21 (539 μm)	17.91 (455 μm) at 130°	4.31 (109 μm)at 246°
LMB X 24.06 (611 μm)	19.64 (499 μm) at 74°	5.20 (132 μm)at 198°
PCH Y 31.50 (800 μm)	29.00 (737 μm) at 49°	6.10 (155 μm)at 209°
PCH X 30.60 (777 μm)	28.20 (716 μm) at 284°	5.10 (130 μm) at 42°

Refer to Figures 9 through 14 for the Orbit/timebase representations of this data.

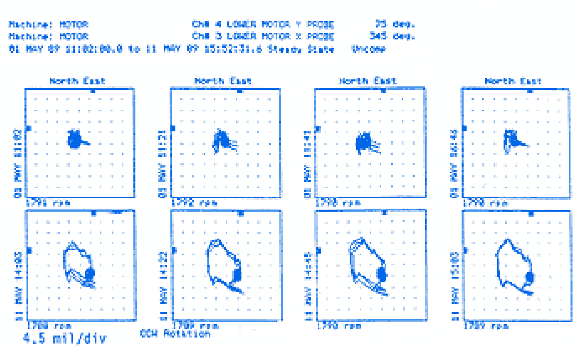

Figure 3

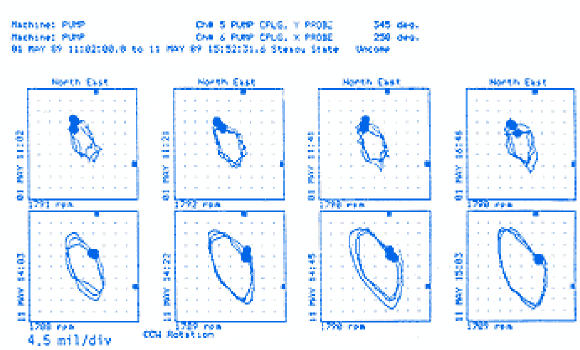

Figure 4

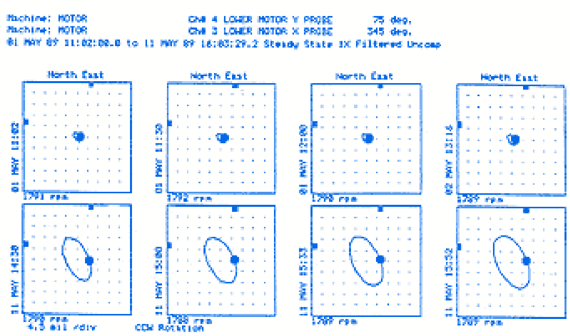

Figure 5

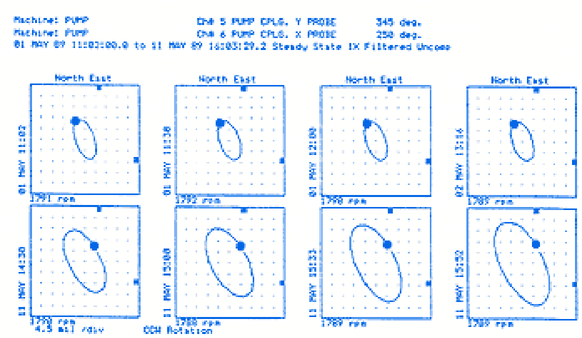

Figure 6

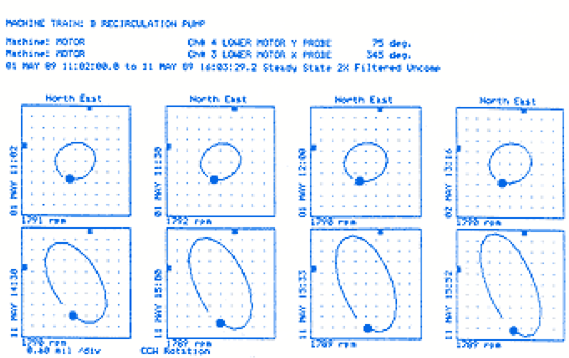

Figure 7

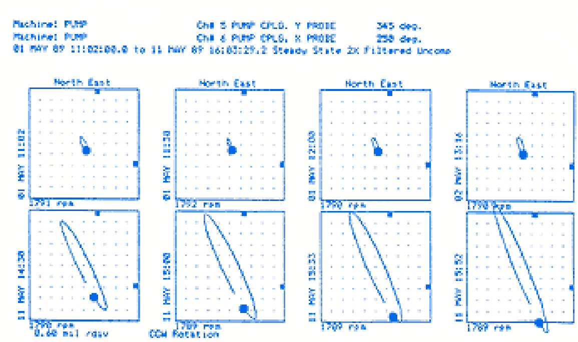

Figure 8

The shaft Orbits are all oriented as if one were standing on top of the motor, facing northeast and looking down toward the pump. With this consideration in mind, northeast is a 0°, north is at 45° and east is at 315°. (Figures 1 and 2.) The expected radial preload on the impeller for the flow conditions that the B pump was experiencing would be a force vector pointing toward 45°, i.e. east.

The shaft Orbits of the B pump indicate that a preload does exist in the eastwest plane. Although the Orbit does not indicate the direction of the preload, the elliptical shape of the Orbit does indicate the presence of a preload.

However, by viewing the 11 May unfiltered Orbits at the pump coupling, one can conclude that the radial side load acts at 45°. Initially, the unfiltered Orbit is elliptical (Figures 3&4). Over the following two hours, the elliptical shape of the Orbit began to truncate on its east side, indicating the shaft was preloaded in that direction.

Figures 15 through 18 are Amplitude and Phase versus Time (APHT) plots for both the 1X and the 2X vectors. At all locations, the amplitude and phase information was constant during the 26 hour period spanning 1 and 2 May. However, significant and continuous changes in both the 1X and 2X vectors were noted during a two hour period on 11 May.

In the presence of a steady state radial force, the crack will affect the rotor in two ways. First, it causes the rotor to bow which is reflected as a change in the 1X response. Secondly, it introduces an asymmetric rotor stiffness which is reflected as a change in the 2X response.

The 2X component is generated during shaft rotation when there are two significant changes of rotor stiffness in the direction of the steady state radial force during each shaft revolution. The shaft deflects less when the stiffness cross section is oriented toward the radial force and deflects more when the weakest cross section is oriented toward the radial force.

It is therefore necessary to monitor the 1X and 2X steady state vectors on a continuous basis to establish the normal Acceptance Region on the APHT plot. Additionally, alarms are necessary in order to alert the user to amplitude and phase deviations outside of the normal Acceptance Region. When either the 1X or 2X vector moves outside the established Acceptance Region, further diagnosis becomes necessary. Continuous changes in the 1X and 2X vectors (Figures 15 through 18) are key indicators of the presence of a shaft crack.

Startup data

Startup data acquired on 1 May indicated that the rotor system's first balance resonance occurred at 1360 cpm with additional resonance responses observed at 2540 cpm, 3550 cpm and 6550 cpm. The resonances were documented by observing the 1X, 2X and 5X vibration response during the startup period. Figure 19 is the 2X response. Figure 20 is the 5X response at the pump coupling. The resonance responses are all significant as they not only indicate at what frequency the rotor resonances were observed, but also that the 2X and 5X resonance responses are in excess of 2.0 mils (51 μm) peak-to-peak and in some instances are in excess of 4.0 mils (102 μm) peak-to-peak.

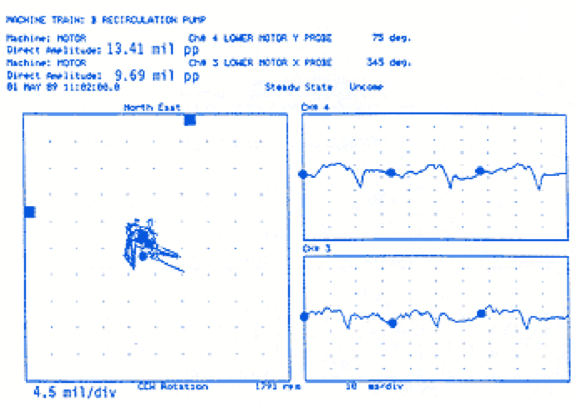

Figure 9
Orbit/Timebase data prior to final crack propagation

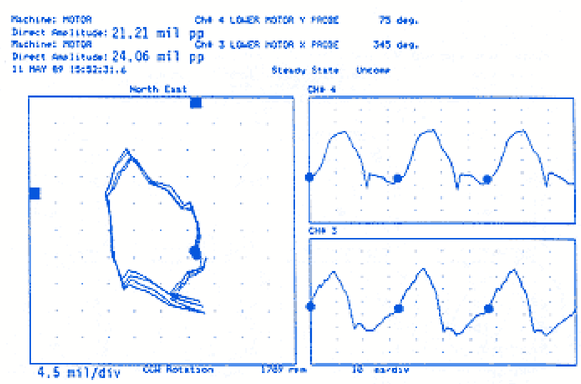

Figure 10
Orbit/Timebase data during final crack propagation

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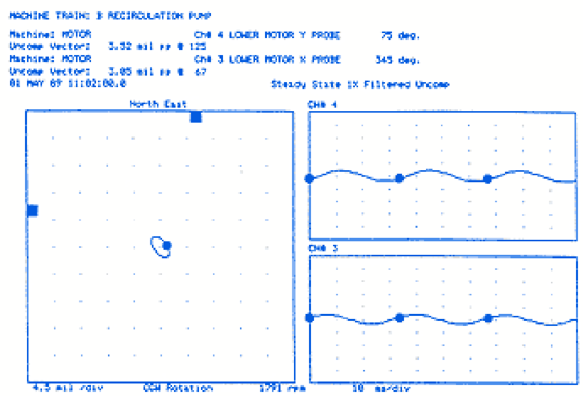

Figure 11
Orbit/Timebase data prior to final crack propagation

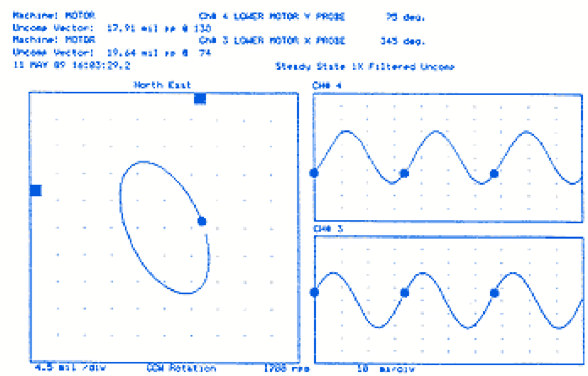

Figure 12
Orbit/Timebase data during final crack propagation

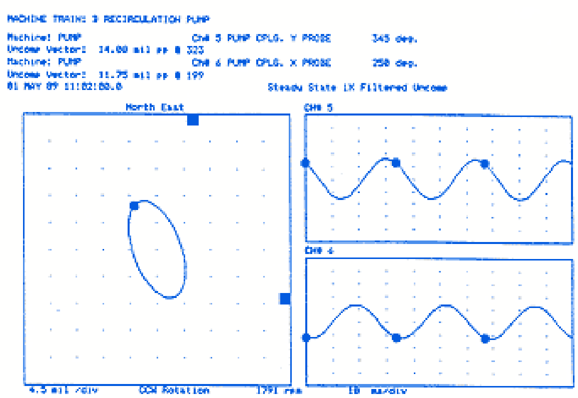

Figure 13
Orbit/Timebase data prior to final crack propagation

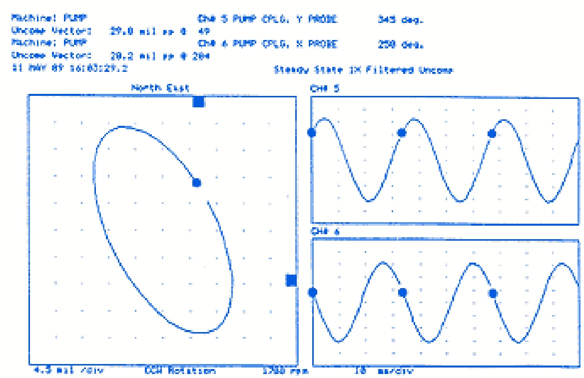

Figure 14
Orbit/Timebase data during final crack propagation

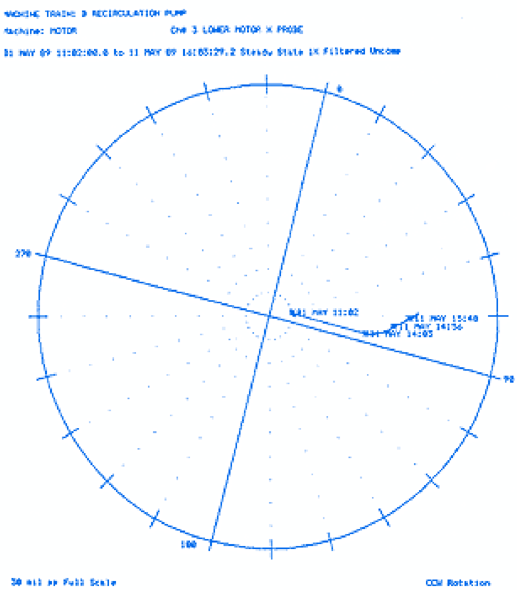

Figure 15
Amplitude and Phase versus Time Plot for 1X vector

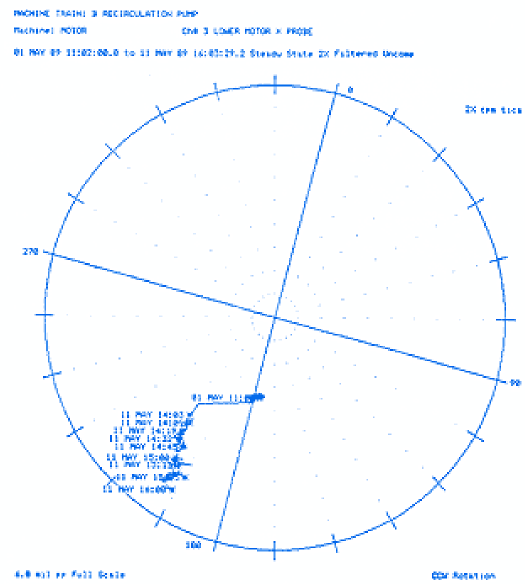

Figure 16
Amplitude and Phase versus Time Plot for 2X vector

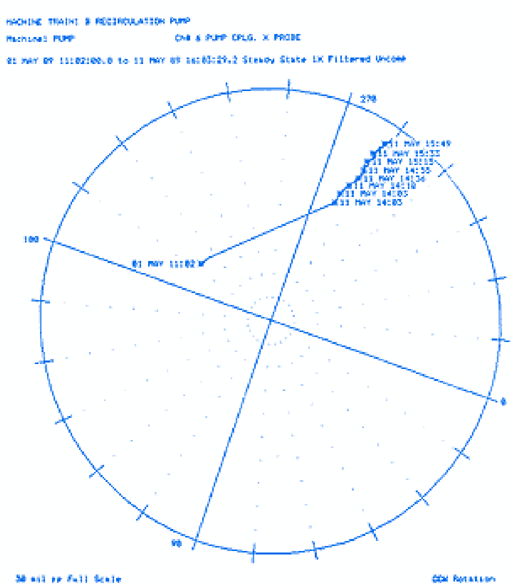

Figure 17
Amplitude and Phase versus Time Plot for 1X vector

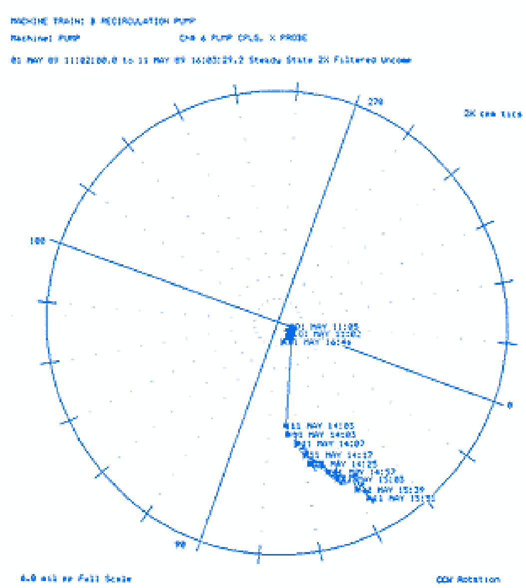

Figure 18
Amplitude and Phase versus Time Plot for 2X vector

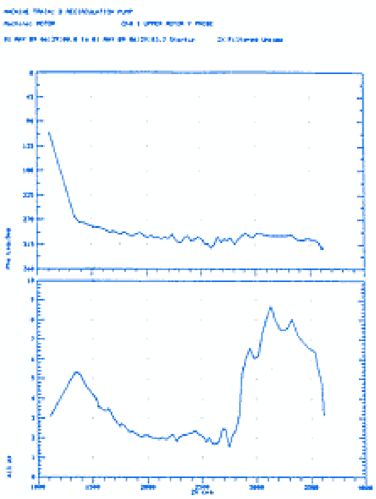

Figure 19

Conclusions

The transient response of the rotor should be documented to determine the balance resonance frequencies. Decreases in a balance resonance frequency indicate that the system stiffness has decreased, an indication of a possible shaft crack.

The startup data for the B pump shows significant 2X and 5X resonance activity. The transient 2X and 5X activity observed on the B pump is the direct result of reduced shaft stiffness due to the existence of the crack during startup on 1 May.

To properly monitor a rotor system for a shaft crack, it is necessary to continuously monitor and trend the overall amplitude, the 1X amplitude, the 1X phase, the 2X amplitude and the 2X phase and to be able to alarm on any one or any combination of these variables. If these variables had been trended at Grand Gulf, all five variables, as observed by ***both pump coupling proximity probes***, would have been in alarm on 11 May.

Changes in the steady state response from 2 through 11 May 1989 clearly indicate the presence of a transverse crack in the rotor system. On 11 May, the 1X amplitudes at the pump coupling had increased by 35% over their values on 2 May, with an associated phase shift of approximately 76°. Significant changes were also noted in the 2X response where the amplitudes at the pump coupling had increased by between 300 and 400%, with associated phase shifts of 52° and 37° respectively on the Y and X probes. As the pump was operated at 1792 rpm on 11 May, the 1X amplitudes increased by an additional 67% and the 2X amplitudes increased by 200%. Two hours later, the overall amplitude at the pump coupling was approximately 32 mils (813 μm) peak-to-peak.

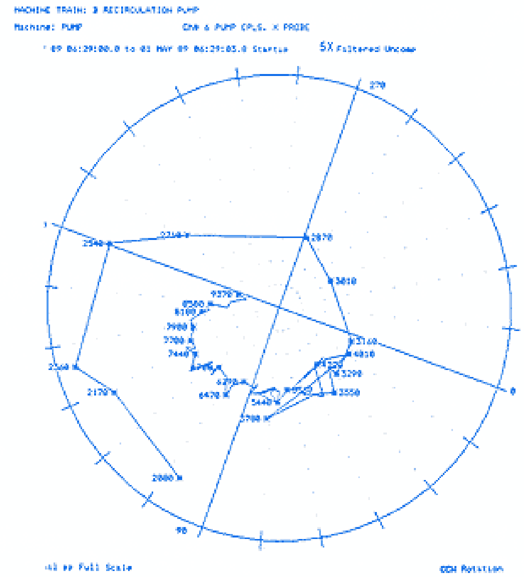

Figure 20

Acknowledgements

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